11th European Space Weather Week - ESWW 11
Liege, Belgium, November 17 – 21, 2014

University of Oulu, Finland | University of Bucharest, Romania | Institute of Space Science Romania | FP7 STORM Project

An Integrated Nonlinear Analysis library - (INA) for solar system plasma turbulence

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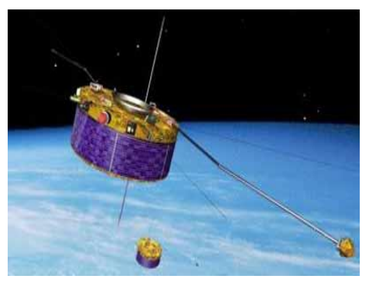
ABSTRACT.

We present an integrated software library dedicated to the analysis of time series recorded in space and adapted to investigate turbulence, intermittency and multifractals. The library is written in MATLAB and provides a graphical user interface (GUI) customized for the analysis of space physics data available online like: Coordinated Data Analysis Web (CDAWeb), Automated Multi Dataset Analysis system (AMDA), Planetary science archive (PSA), World Data Center Kyoto (WDC), Ulysses Final Archive (UFA) and Cluster Active Archive (CAA). Three main analysis modules are implemented in INA: Fourier, Wavelet and PDF analysis. The layered structure of the software allows the user to easily switch between different modules/methods while retaining the same time series for the analysis. The Fourier analysis module includes algorithms to compute and analyze the Power Spectral Density (PSD) and the Spectrogram. Wavelet analysis includes algorithms to compute the Scalogram, the Local Intermittency Measure (LIM) and the Flatness parameter. The PDF analysis module includes algorithms for computing the PDFs for a range of scales and parameters fully customizable by the user; it also computes the Flatness parameter and enables fast comparison with standard PDF profiles like, for instance, the Gaussian PDF. The integrated software library has been tested on several Cluster and Venus Express data and we will show relevant examples. Parts of the library were also used to systematically analyze solar wind and planetary data within the STORM FP7 project (Solar system plasma Turbulence: Observations, inteRmittency and Multifractals). Image catalogues of the results are available through the project website at http://www.storm-fp7.eu/. Research supported by the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement no 313038/STORM, and a grant of the Romanian Ministry of National Education CNCS UEFISCDI, project number PN-II-ID-PCE-2012-4-0418.

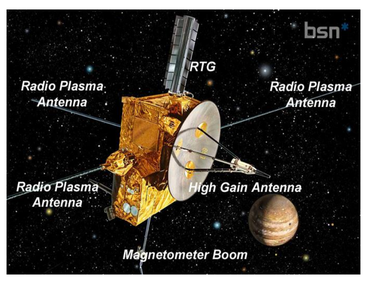
CLUSTER



Launch date:
16.07 and 09.08.2000
Mission end: 31.12.2016
Orbit: Elliptical polar orbit; period: 57 hours
http://sci.esa.int/cluster/

Cluster investigates the Earth's magnetic environment and its interaction with the solar wind. Four identical spacecraft carry advanced scientific instruments that measure the magnetic and electric fields, the density, temperature, the flow velocity and the composition of the terrestrial plasmas. Within STORM, Cluster helps us to understand how the plasma turbulence in the Earth's magnetosphere depends on the solar wind variability.

ULYSSES



Launch date: 06.10.1990
Mission end: 30.06.2009
Orbit: 3 successful passes above the Sun's South and North poles
ulysses.jpl.nasa.gov/1

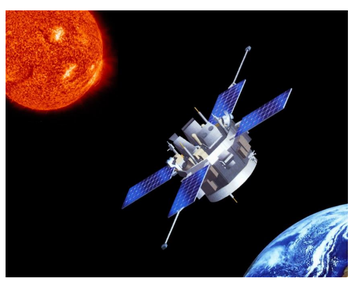
Ulysses is the first satellite that provided measurements above the Sun's poles. The scientific instruments on board Ulysses measure solar wind ions and electrons, magnetic fields, energetic particles, cosmic rays, cosmic dust and interstellar neutral gas. The spacecraft is in orbit around the Sun with a period of 6.2 years. Three sets of polar passes were completed during its operational lifetime: in 1994/1995, 2000/2001 and 2007/2008. In STORM we use data from Ulysses to characterize the solar wind turbulence.

VENUS EXPRESS

Launch date: 09.11.2005
Mission end: 31.12.2016
Orbit: 24-hour elliptical, quasi-polar orbit
sci.esa.int/venus-express/

Venus Express is the European mission to Venus, the second planet from the Sun. Venus Express is equipped with scientific instruments meant to measure the composition of Venus plasma and neutral atmosphere, and the electromagnetic environment. VEX provides data that helps to answer key questions related to the geological past and present of Venus, and to planet's response to solar variability.

ACE



Launch date: 25.08.1997
Mission end: ~2024
Orbit: L1
http://www.srl.caltech.edu/ACE/

The Advanced Composition Explorer (ACE) spacecraft carrying six high-resolution sensors and three monitoring instruments samples low-energy particles of solar origin and high-energy galactic particles. ACE orbits the L1 libration point at about 1.5 million km from Earth. From its location at L1 ACE has a prime view of the solar wind, interplanetary magnetic field and higher energy particles accelerated by the Sun. ACE also provides near-real-time 24/7 continuous coverage of solar wind parameters and solar energetic particle intensities (space weather).

Fourier analysis

There are two main types of Fourier based analyses often used in the context of space plasma physics: Power Spectral Density estimation (PSD) and the Spectrogram representation. The PSD gives an estimate of the distribution over frequency of the power contained in a signal and the spectrogram shows the time evolution of that power. The user can perform these analyses with a wide range of analysis parameters, like: window type, segment length, overlapping percent and others. The program also has an advanced slope analysis module which gives the user the possibility to compute and represent up to 3 linear fits on the same spectrum.

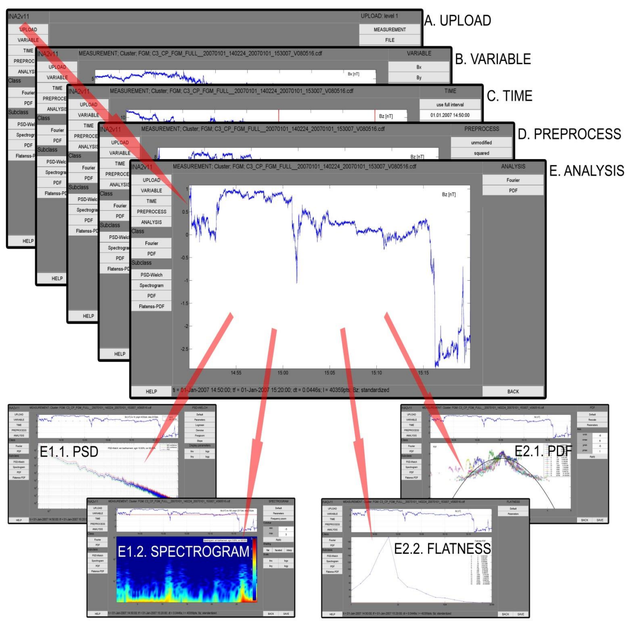
Wavelet analysis

The Scalogram is a representation of PSD over time and scale. Local Intermittency Measure (LIM) is defined as the normalized power at each point in time with respect to the mean power over each scale. Providing a time-scale picture of departures from the mean power spectrum, LIM can be used to detect intermittent events. Our program provides an easy to use interface where the user can choose parameters like: the wavelet function, minimum and maximum scales, and others, and also takes care of the graphical representation of the results. In order to have a flexible display output, we also provide settable display parameters (like colorbar limits, shading type and others).

PDF analysis

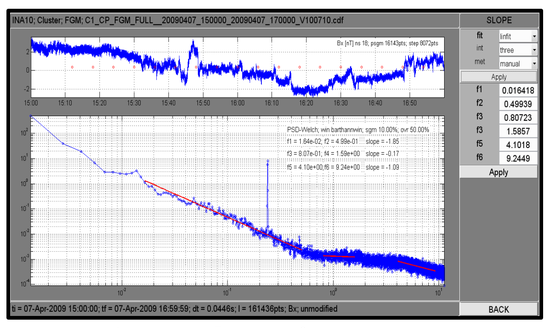
Having a generic signal Q(t), the method first computes the differences between measurements separated by the scale τ ($\Delta Q_\tau(t) = Q(t+\tau) - Q(t)$), then the normalized histograms of these differences gives $P(\tau)$, the Probability Distribution Function (PDF) of fluctuations at scale τ. The shape of the PDFs can be characterized by a single parameter called the Flatness factor, defined in terms of PDF moments as the fourth moment divided by the square of the second moment. The program also gives a wide variety of settable display parameters, like the axis limits, for example.

Diagram representation



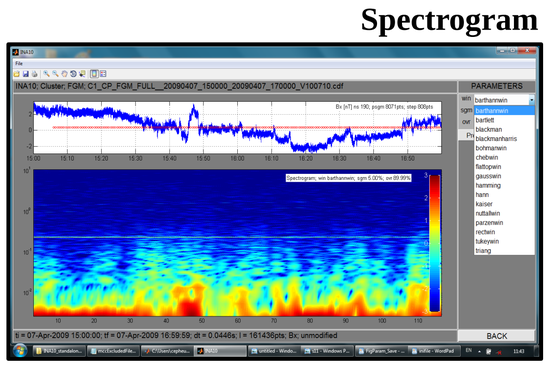
Overview

We have developed a software library that cumulates the programs developed to read and process data files from the online databases targeted by the STORM FP7 project: Cluster, Ulysses, Venus Express and ACE spacecraft and also Geomagnetic Indices. There is also a list of synthetic signals which can be analyzed. For other file types we implemented general ascii, cdf and mat reading routines. The collection of analysis codes is embedded in a Graphical User Interface (GUI) in order to create a user-friendly and highly configurable analysis environment.

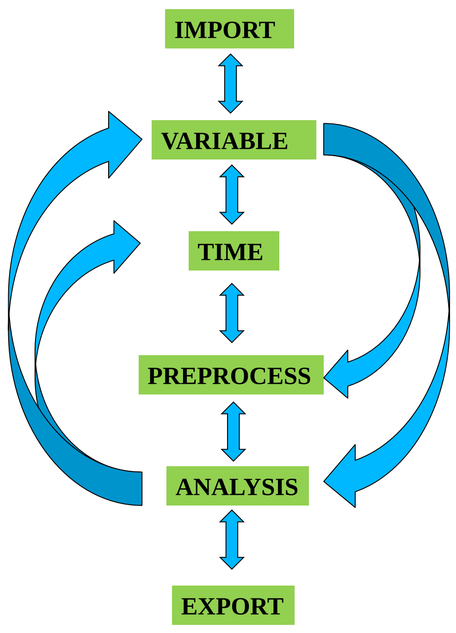


Power Spectral Density | **Scalogram** | **Probability density functions**

Spectrogram | **Local Intermittency Measure** | **The Flatness factor**



Workflow chart



Technical details

INA and the related analysis codes are written in Matlab (Release 2013a), one of the most common programming tools within the space science community. Besides the main Matlab environment, the following Matlab toolboxes have been used in INA: (1) Signal Processing Toolbox, (2) Statistical Toolbox, (3) Matlab Compiler. The software takes advantage of a large number of matlab built-in functions: : pwelch, spectrogram, cwt etc. In order to facilitate the usage of INA outside the Matlab environment, an executable standalone version is compiled. The Matlab Compiler Runtime (MCR_R2013a) must be installed in order to use the standalone version. MCR_R2013a is freely accessible from the MathWorks website at: http://www.mathworks.com/products/compiler/mcr/. For the moment, only the Windows 64-bit version executable was built, but we plan to compile the code also for Linux and Mac OS.

Summary and conclusions

We developed a computer program specifically designed for the analysis of space physics data. The graphical user interface of the software is designed to be easy to use also by scientist not specialized in time series analysis tools and by young researchers. There are three main classes of analysis methods implemented in the software: Fourier, Wavelet and Probability distribution Functions. As part of the Fourier Analysis module the user can compute Power Spectral Densities (PSDs) and Spectrograms using a very wide range of parameters (the window type, the segment length, the overlap between adjacent segments, and others). The Wavelet analysis methods implemented in the program are: the Scalogram and Local Intermittency Measure. Within the PDF Analysis part of the program the user can compute PDFs on multiple scales and also the Flatness factor, which is a measure of the shape of the PDF.

The program was developed within the context of the FP7 STORM project, and the final version will be made freely available to the scientific community at the end of the project (2016). A beta version of the software is already available through the project website at: http://www.storm-fp7.eu/

Acknowledgements

Research supported by the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement no 313038/STORM, and a grant of the Romanian Ministry of National Education, CNCS UEFISCDI, project number PN-II-ID PCE-2012-4-0418.